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ESTIMATION OF STOL A/C TAKE-OFF DISTANCES

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SUMMARY

This study was undertaken to find an easy-to-use take-off distance prediction method and to evaluate its applicability to STOL aircraft. For the purposes of this present study STOL aircraft were defined as those requiring a take-off ground roll of less than 1000 ft.

Two existing take-off ground roll estimate methods were evaluated by comparing predicted values with available data for several STOL aircraft. The resulting accuracies were respectively within 9% and 11% error.

It was found that one of these methods could be further simplified and yet still yield acceptable results. That is, excluding two predictions this simplified method yielded an accuracy within 13% error.

In addition, some correlation was found to exist between short take-off ground roll and total distance over a 50 ft obstacle. As a result an expression was derived relating the two.

INTRODUCTION

In many preliminary studies and analyses of new aircraft systems it is necessary to predict take-off distances before detailed characteristics of the aircraft are available. As a result, approximate methods requiring a minimum of input data are very heavily relied upon. A number of these reliable quick-estimate methods are presently employed for conventional "long" take-off aircraft and it was the purpose of this study to review these methods for application to STOL aircraft. For the purposes of this present study STOL aircraft are defined as those requiring a ground roll of less than 1000 ft.

STOL aircraft take-off distance predictions yielded by a number of quick-estimate methods were compared with available STOL aircraft data. Two of these methods predicting take-off ground roll were selected for further evaluation and will be discussed herein. In addition, a correlation between take-off ground roll and total distance over a 50 ft obstacle is shown. An equation relating the two was developed to obtain for a given ground roll a first approximation of total take-off distance over a 50 ft obstacle.

DISCUSSION

HARTMAN METHOD

The Weapon Systems Analysis Office has long used a reasonably accurate quick-estimate method for predicting take-off ground roll distance for conventional "long" take-off aircraft. Reference 1 presents this method which originally appeared in a NACA report, reference 2, by E. P. Hartman. It is derived from the fundamental equation for aircraft ground roll,

$$S = W/g \int_0^{V_{TO}} (V/F)\, dV$$

with the assumption that the effective force, F, which is a function of velocity can be evaluated at an average velocity. This led to

$$S_{GR} = \frac{W\, V_{TO}^2}{64\, F_{V_{AVG}}}$$

Hartman showed that for all conventional take-off aircraft during the ground run the inverse of the acceleration varies almost linearly with the square of the velocity. As he pointed out in reference 2 this was the basis for the use of an average velocity equal to 0.707 V_{TO} in evaluating $F_{V_{AVG}}$. Therefore Hartman's method as presented in reference 1 is outlined as follows.

$$S_{GR} = \frac{W\, V_{TO}^2}{64\left[T-D-\mu(W-L)\right]}$$

where S_{GR} = take-off ground roll (ft)
- W = take-off gross weight (LBS)
- V_{TO} = aircraft velocity at take-off (ft/sec)
- T = take-off thrust at $0.7V_{TO}$ (LBS)
- D = drag at $0.7V_{TO}$, ground attitude
- μ = coefficient of rolling friction
- L = lift at $0.7V_{TO}$ ground attitude

The above inputs, in most cases, during the preliminary design stage are readily available or can be estimated with reasonable accuracy.

Aerodynamic and performance data for a limited number of propeller-driven STOL aircraft were compiled and applied to Hartman's method in order to compare the predicted ground rolls with flight test values. Standard Aircraft Characteristics chart ground rolls, although not necessarily based on flight test, are official service estimates and were used where explicit flight test values were not available. As shown in figure 1, the predicted ground roll was plotted versus a flight test or SAC chart value. Each aircraft with the exception of the Helio Courier, Breguet 941, and the C-130E is represented by three ground rolls at various gross weights. These exceptions, which are due to the limited amount of data available, are represented by only one ground roll. It is evident that all predictions as indicated by the 5% and 10% error bands are within 9% of the flight test values.

KETTLE METHOD

D. J. Kettle, in the January, 1958 issue of Aircraft Engineering presented a method for estimating ground roll distance at take-off (and landing). Essentially this method consisted of a solution for the basic ground roll expression

$$S = \frac{W}{g}\int_{0}^{V_{TO}} \frac{V dV}{T - D - \mu(W-L)}$$

which led to

$$S = \frac{30\,W/S}{\sigma\,(C_{D_{GR}} - \mu C_{L_{GR}})} \log_{10}\left\{\frac{T/W - \mu}{[(T/W) - \mu] - [(C_{D_{GR}} - C_{L_{GR}})/C_{L_{TO}}]}\right\}$$

Kettle's graphical solution for this cumbersome expression is partially reproduced in figure 2 and it is seen that this chart was constructed using $(T/W) - \mu$, $(C_{D_{GR}} - \mu C_{L_{GR}})/C_{L_{TO}}$, $C_{L_{TO}}$, and W/S as input parameters. It is worth noting that Kettle suggested that the thrust, T, be calculated at $0.7V_{TO}$ which incorporates the average velocity used by Hartman. To illustrate the use of Kettle's chart the following approximate data are given for an aircraft at standard day, sea level conditions.

$C_{D_{GR}} = 0.23$ $\quad$ $C_{L_{TO}} = 2.10$

$C_{L_{GR}} = 1.60$ $\quad$ $\sigma = 1$

$W/S = 45 \text{ lb/ft}^2$ $\quad$ $T_{.7V_{TO}} = 5920 \text{ lbs}$

$\mu = 0.025$ $\quad$ $T/W = 0.395$

$W = 15{,}000 \text{ lbs}$ $\quad$ $\mu C_{L_{GR}} = 0.040$

$(T/W) - \mu = 0.370$ $\quad$ $(C_{D_{GR}} - \mu C_{L_{GR}})/C_{L_{TO}} = 0.090$

$C_{L_{TO}} = 2.10$ $\quad$ $W/S = 45$

These above inputs are applied as indicated by the dashed line in figure 2. The resulting prediction is seen to be 870 ft. As was true of the Hartman case the above input data, in general, during the preliminary design stage are readily available or can be estimated with reasonable accuracy.

Using the basic STOL aircraft data compiled to evaluate the Hartman method, the inputs for the Kettle method were also derived and applied to the chart in figure 2. For convenience the $C_{L_{GR}}$ and $C_{D_{GR}}$ for the Kettle method were taken at 0.7 V_{TO}. Using the same number of aircraft and procedures as for figure 1, the resulting predictions were plotted in figure 3. As shown, all predictions were within 11% error.

In order to compare the predictions of both methods, table I contains for each aircraft gross weight their respective T.O. ground roll estimates. (The data points in figures 1 and 3 were taken from this tabulation).

Due to the lack of available STOL jet aircraft data both of the above methods were evaluated with only propeller-driven aircraft. It is stressed, however, that this should not necessarily preclude their application to jet aircraft. The Hartman method, in fact, is presently used successfully with conventional "long" take-off jet aircraft. The Kettle method which was derived from the same basic ground roll equation with no major assumptions should be equally as applicable.

SIMPLIFIED HARTMAN METHOD

Admittedly, even the relatively simple inputs required for the take-off prediction methods discussed above are sometimes difficult to obtain. To determine the effective thrust used in the Hartman method, for example, a knowledge of both take-off thrust and drag at 0.7 of the take-off speed is required.

Upon examining the STOL aircraft data compiled for the Hartman method it was found that on the average an aircraft's take-off effective thrust at $0.707V_{TO}$ was approximately 70% of its take-off static thrust. Using this observation in the form of an assumption (i.e. $T_e = 0.7T_o$) with the basic ground distance expression used by Hartman, ground runs were estimated for a limited number of STOL aircraft. In a manner similar to figure 1, figure 4 indicates the accuracy of these predictions. As shown, only two predictions fell beyond 13% error. It is therefore evident that this further assumption ($T_e = 0.7T_o$) as indicated by the aircraft data applied still allowed one to make a reasonably accurate, rapid estimation of take-off ground roll.

It is noted, however, that the significant difference between the rate of jet and propeller-driven aircraft thrust degradation during take-off ground roll prevents the application of this simplified Hartman method to jet aircraft. It appears that for this latter application the average aircraft effective thrust is typically a higher percentage of static thrust than it is for propeller-driven aircraft. Due to the lack of sufficient STOL jet aircraft data available for this present study, no attempt could be made to determine a meaningful average percentage value for jet aircraft.

TOTAL TAKE-OFF DISTANCE

Estimating climb distance over a 50 ft obstacle with a method comparable to the simplicity and accuracy of the Hartman or Kettle ground roll methods appears to be virtually impossible. The climb distance, which is mathematically more complicated, cannot be accurately predicted via a general quick-estimate method. This study reviewed two very simple total take-off distance over a 50 ft obstacle methods and found that they yielded unacceptable accuracies. Errors up to 30% and 50%, respectively, were experienced and, therefore, they were not given any further consideration.

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In view of this difficulty in estimating climb distance, reference 1 plotted for a large number of conventional "long" take-off aircraft, ground roll versus total take-off distance over a 50 ft obstacle and with the resulting linear relation formulated an expression for predicting the total take-off distance. In order to obtain a similar expression for STOL aircraft, the same procedure was followed in figure 5, in that for a number of STOL aircraft, ground run was plotted versus total take-off distance. All of the points represent propeller-driven aircraft with ground rolls less than 1,000 ft and total take-off distances less than 1600 ft. Where the available data made it possible, all of the aircraft were represented by three points, that is, take-off distances at three gross weights. It is noted that this figure contains a great many more data points for STOL aircraft than previous figures since only take-off ground roll and total take-off distance were required for these data points. A line having the equation $S_{TOT} = S_{GR}^{0.88}$ was found to give a reasonably good correlation with these data points. Given a ground roll distance less than 1000 ft for a conventional take-off aircraft this expression may be used as a first approximation of the total take-off distance over a 50 ft obstacle.

CONCLUSIONS

Two methods for rapidly estimating the ground roll distance during take-off appear to yield acceptable results on the basis of comparison with a limited sample of STOL aircraft test data.

1. The Hartman method for estimating take-off ground roll yielded predictions that were within 9% error.

2. The Kettle method for estimating take-off ground roll yielded predictions that were within 11% error.

3. The Hartman method further simplified by the assumption that the take-off effective thrust equals 70% of the take-off static thrust yielded predictions, with two exceptions, within 13% error.

4. No solution comparable to the simplicity or accuracy of above methods was found to exist for total take-off distance over a 50 ft obstacle. The expression $S_{TOT} = 4\ S_{GR}^{0.88}$ which is based on a correlation, can be used as a first approximation to the total take-off distance.

REFERENCES

1. "Aircraft Preliminary Design Methods Used in the Weapon Systems Analysis Division." Hugo Sheridan, Report No. R-5-62-13, Bureau of Naval Weapons, June, 1962

2. "Considerations of the Take-Off Problem." NACA Technical Note 557, E. P. Hartman, 1936

3. "Ground Performance at Take-Off and Landing." D. J. Kettle, Aircraft Engineering, January, 1958

4. Standard Aircraft Characteristics, NAVWEPS 00-110A-1DD, Department of Navy.

5. Standard Aircraft Characteristics, AFG2, Volume II, Air Force Systems Command, Research and Technology Division.

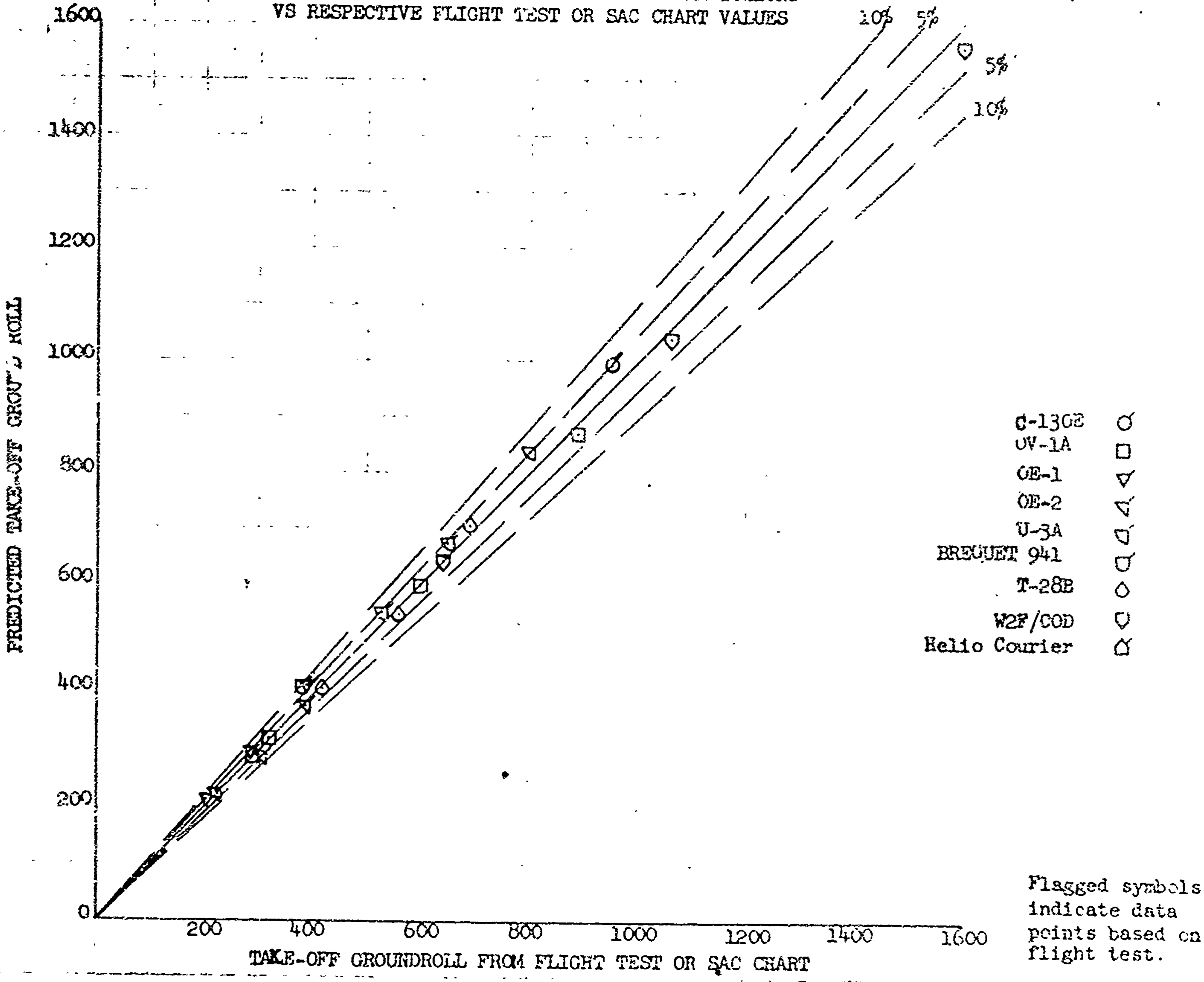
TABLE I

COMPARISON OF HARTMAN AND KETTLE TAKE-OFF GROUND ROLL PREDICTIONS

AIRCRAFT	GROSS WEIGHT (LBS)	TAKE-OFF GROUND ROLL (FT) HARTMAN	KETTLE	FLIGHT TEST OR SAC CHART
C-130E	100,000	992	1,000	950 *
W2F/COD	40,000	641	645	642
"	48,000	1038	1,050	1,060
"	56,000	1,561	1,543	1,600
BREGUET 941	35,600	416	409	380 *
HELIO COURIER	2,800	290	300	290 *
T-28B	7,400	412	375	420
"	8,000	545	540	560
"	8,600	706	675	690
OE-1	1,800	213	195	204 *
"	2,100	300	300	285 *
"	2,400	419	405	390 *
OE-2	2,100	226	225	225 *
"	2,400	291	300	309 *
"	2,650	382	375	389 *
OV-1A	10,000	325	300	320
"	13,000	598	570	600
"	15,000	871	850	890
U-3A	4,000	548	532	530 *
"	4,400	673	634	650 *
"	4,830	838	842	800 *

* Flight Test

FIGURE 1. HARTMAN METHOD TAKE-OFF GROUND ROLL PREDICTIONS VS RESPECTIVE FLIGHT TEST OR SAC CHART VALUES



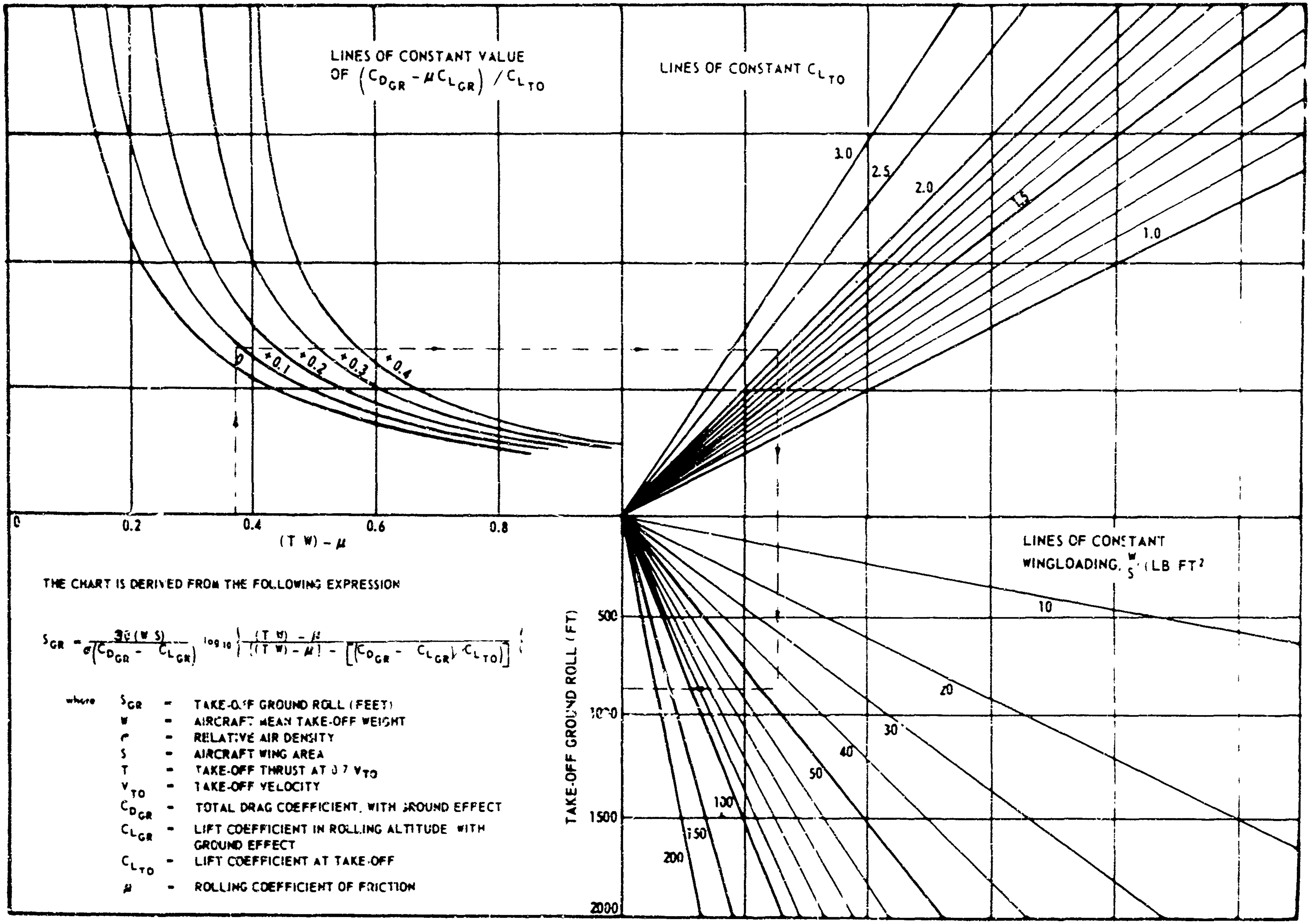


FIGURE 2. KETTLE METHOD FOR ESTIMATING TAKE-OFF GROUND ROLL

FIGURE 3. KETTLE METHOD TAKE-OFF GROUND ROLL PREDICTIONS VS RESPECTIVE FLIGHT TEST OR SAC CHART VALUES

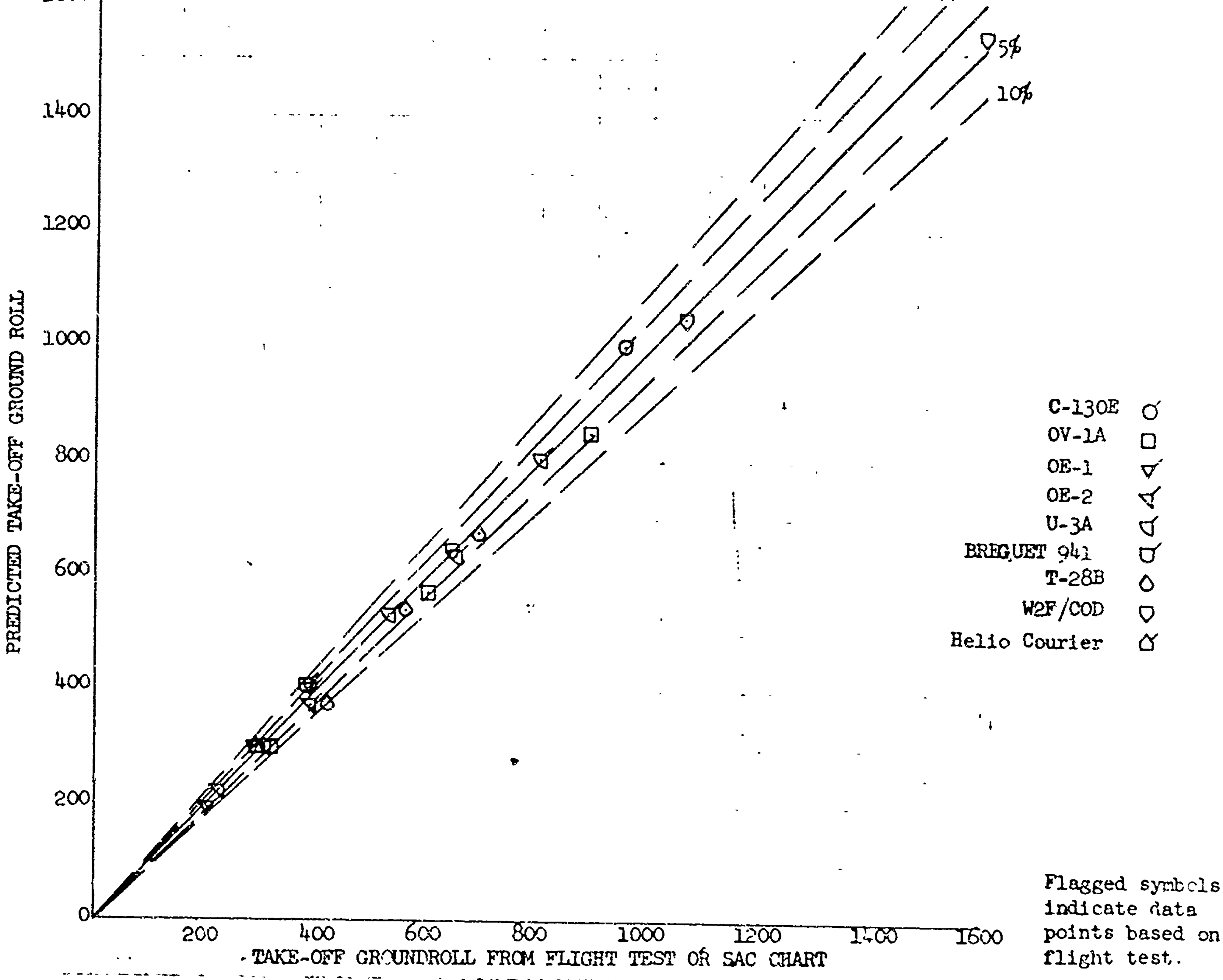


FIGURE 4, SIMPLIFIED HARTMAN METHOD TAKE-OFF GROUND ROLL PREDICTIONS VS RESPECTIVE FLIGHT TEST OR SAC CHART VALUES

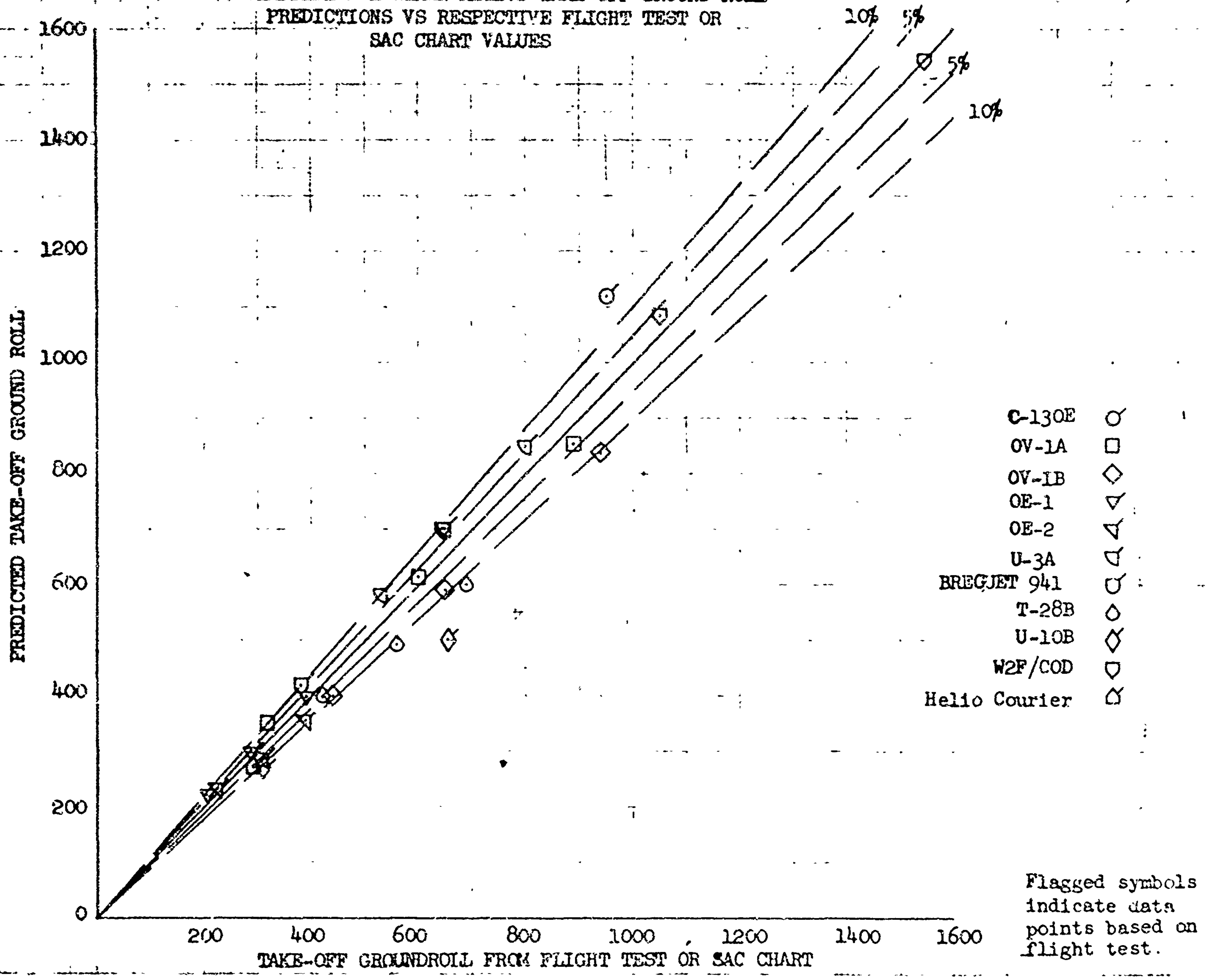


FIGURE 5. TAKE-OFF GROUND ROLL VS TOTAL TAKE-OFF DISTANCE OVER A 50 FT OBSTACLE